

Large Satellites: Active Worlds and Extreme Environments

Of the six large outer-planet satellites—Io, Europa, Ganymede, Callisto, Titan, and Triton—all are larger than Pluto and two are larger than Mercury; in addition, there are 11 medium-sized satellites (Figure 5.1; Table 5.1). Each planet-sized satellite is unique:

- Io is intensely volcanically active,
- Europa may have a layer of subsurface water greater in volume than all of Earth's oceans combined,
- Ganymede has an intrinsic magnetic field,
- Callisto is largely undifferentiated,
- Titan has a thick atmosphere rich in organic compounds, and
- Triton has active, geyserlike eruptions.

The large satellites have bizarre life cycles, influenced by orbital evolution and tidal heating, revolutionizing concepts based on the terrestrial planets. They are rich in volatile species such as H_2O , SO_2 , N_2 , CH_4 , CO_2 , and perhaps NH_3 , creating a rich diversity of processes and environments. The 11 medium-sized satellites are also unique worlds, and they may provide essential information about the origin and evolution of satellite systems.

FIGURE 5.1 (*facing page*) The 17 large and medium-size satellites of the outer planets, shown to scale, are worlds in their own right. The Galilean satellites of Jupiter (*top row*) are (*from left*) Io, whose surface is constantly renewed by active volcanoes tinged with sulfur allotropes; Europa, which probably possesses a liquid water ocean beneath its ruddy ice skin; Ganymede, a moon bigger than the planet Mercury, possessing a rutted surface of dirty ice and an internally generated magnetic field; and Callisto, a moon with an ancient cratered surface whose interior is only weakly differentiated. Saturn's family of bright icy moons (*second row*) consists of Mimas, Enceladus, Tethys, Dione, and Rhea; cloud-shrouded Titan has an atmosphere rich in organics and possibly seas of methane; and two-toned Iapetus shows one face as bright as snow and the other as black as coal. The five major uranian satellites (*third row*) are Miranda, Ariel, Umbriel, Titania, and Oberon. Each displays a dirty-ice surface and some tectonic activity, but the bizarre world of Miranda—with its exotic jumble of surface terrains suggesting that it may have been totally disrupted in the past and put back together at random—steals the show. Neptune's sole large satellite (*fourth row*), Triton, is coated with exotic ices tinged pink by organic molecules; nitrogen geysers spew high into its tenuous atmosphere. Courtesy of NASA/JPL.

TABLE 5.1 Large- and Medium-Sized Satellites of the Outer Solar System

Planet	Satellite	Semimajor Axis (10^3 km)	Rotation Period (days)	Diameter (km)	Mass (10^{20} kg)	Density (kg/m^3)
Jupiter	Io	422	1.77	3,643	893	3,500
	Europa	671	3.55	3,120	480	3,000
	Ganymede	1,070	7.15	5,276	1,482	1,900
	Callisto	1,883	16.69	4,820	1,076	1,800
Saturn	Mimas	186	0.94	394	0.375	1,200
	Enceladus	238	1.37	502	0.7	1,100
	Tethys	295	1.89	1,048	6.27	1,000
	Dione	377	2.74	1,120	11.0	1,500
	Rhea	527	4.52	1,528	23.1	1,200
	Titan	1,222	15.95	5,150	1,346	1,900
	Iapetus	3,561	79.33	1,435	16	1,000
	Miranda	129	1.41	472	0.66	1,200
Uranus	Ariel	191	2.52	1,158	13.5	1,700
	Umbriel	266	4.14	1,169	11.7	1,400
	Titania	436	8.71	1,578	35.3	1,700
	Oberon	584	13.46	1,523	30.1	1,600
Neptune	Triton	355	5.88	2,705	214	2,100

WHY DO WE CARE ABOUT LARGE SATELLITES?

Why are these large satellites worthy of national and international exploration and research? One good reason is that advancing basic research about physical processes in fields such as volcanology and meteorology may eventually provide benefits that will improve our lives. Another is that such interesting worlds inspire our youth and students to excel in mathematics and science. But the most compelling motivation is to understand the origin and destiny of life. Water is essential to life as we know it, and the large icy satellites may contain the largest reservoirs of liquid water in the solar system. Outside Earth, Europa may be the best place in the solar system to search for extant life. Titan provides a natural laboratory for the study of organic chemistry over temporal and spatial scales unattainable in terrestrial laboratories. Perhaps teeming with life or perhaps sterile today, these worlds do contain the basic ingredients for life. Knowing whether they do or do not harbor life is equally important. The origin and evolution of satellite systems also provide analogs for understanding extrasolar planetary and satellite systems, some of which may be abodes for life.

Origins and Orbital Dynamics

The accretion process that led to the formation of the solar system also led to the formation of satellite systems around the giant planets. The results of four additional accretion “experiments” within the solar system are therefore available for detailed study. The fundamental process of accretion leading to the formation of satellite systems is directly analogous to that leading to the planets, but other processes—for example, gas drag and tidal interactions—may have had more or less important roles in the protoplanetary nebulae. Since the satellites are much too small to capture hydrogen or helium, they provide a record of the inventory of condensable species in the protoplanetary nebulae. The size, distribution, and compositions of the satellites within a system also inform us about the physical and dynamical conditions during accretion. The Galilean satellites, for example, apparently contain a record of the temperature gradient in the nebula in which they formed through their decreasing density with distance from Jupiter (see Table 5.1). Such a trend is not obvious in the other satellite systems. The formation of four large satellites in the jovian system while other systems have at most one is perhaps indicative of a denser nebula around the young Jupiter.

The periodic driving forces of orbital resonances have played an important role in the formation of planetary and satellite systems. This is evident in the dynamics of the outer-planet satellites, many of which are currently involved in orbital resonances. The importance of tidal dissipation in the origin and evolution of resonant configurations is apparent in the jovian system, where Io, Europa, and Ganymede interact through multiple resonances, and where tidal dissipation drives Io's volcanism and may maintain an ocean within Europa. At Saturn, resonances currently exist between the satellite pairs Mimas-Tethys, Enceladus-Dione, and Titan-Hyperion; and at Uranus, paired resonances likely once existed among the satellites Miranda, Ariel, and Umbriel. Resonant configurations are set up by orbital evolution driven by tidal interactions, and the process of evolution into and out of resonance may involve periods of extremely large tidal dissipation, which may significantly affect the satellites' thermal histories and interior structures.

Tidal dissipation can be a long-lived heat source, completely independent of stellar radiation, and it might allow habitable planets or satellites to exist at a much wider range of distances from a much wider range of central stars than previously imagined. Europa, with its plentiful supply of water, may be one of these habitats, an environment that may be far more common in the universe than Earth-like planets orbiting Sun-like stars. Tidal dissipation was probably important to many large satellites, and to the Pluto/Charon system.

Interiors

For the majority of the satellites of the outer solar system, our knowledge of their interiors is limited to the mean density of the satellite (see Table 5.1), but the Galilean satellites, which have been visited by the Galileo spacecraft, are now much better understood. By measuring the tidal and rotational distortion of the satellites, the normalized moments of inertia about the rotation axes have been well constrained, leading to the following conclusions regarding the interiors of the Galilean satellites:¹⁻⁴

- Io is differentiated into a large metallic core, roughly half the satellite's radius, surrounded by a silicate mantle.
- Europa has a 100 ± 25 -km-thick H₂O layer, which is frozen at the surface and may be liquid beneath. The remainder of Europa's interior likely consists of a silicate mantle of density $\sim 3,300 \text{ kg m}^{-3}$, surrounding a metallic core with a radius of $600 \pm 150 \text{ km}$.
- Ganymede's metallic core was detected by the gravity measurements at the same time that its magnetic field was discovered. A model for Ganymede's interior consisting of an Io-sized core and mantle surrounded by 800 km of ice fits the gravity data and accounts for the metallic core required by the magnetic field.
- Callisto is not differentiated like Ganymede, despite the similarity in size and density. A significant metallic core can be ruled out, as can a completely undifferentiated structure. The intermediate value of Callisto's moment of inertia requires a layer of mixed ice and rock, which may extend all the way to the center. These conclusions are based on the reasonable assumption that Callisto is in hydrostatic equilibrium.

The very different fates of Callisto and Ganymede suggest that tidal heating is probably an important factor in satellite differentiation. Titan has undergone at least a partial differentiation resulting in a dense atmosphere of N₂ and other volatiles that are extremely rare or absent in the jovian satellites. Triton is currently degassing volatile species via geysers; moreover, Triton's surface displays evidence for vigorous cryovolcanic and tectonic processes, perhaps reflecting intense tidal heating and differentiation of its deep interior during capture into Neptune orbit.

The surface evolution of the smaller satellites offers intriguing clues about their interiors. Despite their relatively small sizes, Enceladus, Tethys, Ariel, and Titania all seem to have experienced some internally driven surface activity, indicating that internal evolution has occurred. Tiny Miranda has a complex tectonic history, which has likely been modulated by differentiation and/or tidal heating.

The thermal states of the interiors of the outer-planet satellites are coupled to their differentiation. Tidal heating is driving the continuing magmatic activity of Io and the ongoing loss of volatile elements (S, O, Na, K) from Io's surface, which affects the plasma environment throughout the jovian system. Ganymede's differentiated interior and actively convecting core (required to generate its magnetic field) may be a consequence of its passage

into resonance, while Callisto has not experienced this history. The origin and persistence of liquid-water layers in icy satellites depend directly on their thermal histories. Galileo magnetometer observations of induced electrical currents in Europa, Ganymede, and Callisto imply that liquid-water layers exist in all three icy jovian satellites.^{5,6} While the layers in Callisto and Ganymede are bounded by ice on both sides (high-pressure phases of ice are denser than liquid water, resulting in an ice-liquid-ice sandwich), Europa's liquid water—analogue to Earth's deep oceans—is most likely in direct contact with its silicate mantle. Tidal heating in Europa's ice is probably sufficient to stabilize its liquid layer for long periods, but other icy satellites may have only transient liquid layers.

Geological Processes

Cratering

Impact craters serve as probes of satellite crusts, indicators of surface age, and records of the impactor population through time.⁷ Large impacts can penetrate completely through the brittle outer crust of an icy satellite to excavate deep (perhaps oceanic) material and may form a multiringed structure. Very large impacts may fracture a satellite's interior or potentially disrupt a large satellite. Relaxation of crater topography (or the absence of relaxation) can be indicative of the past thermal gradient. High-resolution imaging of the Galilean satellites suggests that the number of small impactors in the outer solar system may be much less than estimates extrapolated from the lunar flux.⁸ One implication is that impact gardening and regolith generation are less effective on outer-planet satellites than on the terrestrial planets.

Sun-orbiting (heliocentric) impactors are expected to produce markedly more craters on the leading hemisphere of a synchronously rotating satellite than on its trailing hemisphere. For the saturnian satellites and Triton, crater size-frequency data show complexities attributable in part to planet-orbiting (planetocentric) impactor populations.^{9,10} Recent flux estimates and dynamical simulations that include the newly recognized effects of Kuiper Belt and Oort cloud cometary impactors indicate higher fluxes and therefore younger satellite surface ages than previously estimated. For example, by these estimates, Triton's plains are on average only ~100 million years old, and Europa's surface is just ~50 million years old.^{11,12} The mounting evidence indicates that some large outer-planet satellites have been active worlds for much of solar system history.

Tectonics

The large satellites display a broad array of tectonic features interpreted as the manifestation of extensional, compressional, and strike-slip deformation.^{13,14} Extensional structures are especially prevalent on many of the mid-sized icy satellites of Uranus and Saturn and on Triton, potentially the manifestation of global expansion during freezing of interior water or differential cooling of their surfaces and interiors. Lanes of subparallel ridges and troughs on Miranda, Enceladus, and Ganymede may share analogous origins as regions of concentrated extension and icy volcanism, analogous to some terrestrial rift zones. Individual ridges on saturnian satellites and sets of ridges on Enceladus may be due to compression, perhaps from global cooling and contraction or from convection.

Galileo imaging of the large jovian satellites has revolutionized our understanding of large-satellite tectonics. Io has mountains that soar to 17 km tall, probably formed as volcanic materials piled onto the surface, placing the entire lithosphere into compression.^{15,16} Callisto shows enormous multiringed structures, which at high resolution consist of normal fault scarps and graben.¹⁷ These and similar concentric structures on Ganymede and Europa probably formed when large impacts penetrated through the satellites' brittle lithospheres to mobile material below—plausibly liquid water. Ganymede displays an array of extensional tectonic structures, notably lanes of bright “grooved terrain,” likely formed by normal faulting of a cold, ice-rich lithosphere above warmer, more ductile ice.¹⁸ Grooved terrain may be linked to satellite differentiation, during which high-density ice polymorphs were displaced from the deep interior resulting in volume expansion of the whole moon.

The varied tectonic styles of Europa hint at a sub-ice ocean (Figure 5.2).¹⁹ The satellite's bright plains are crisscrossed by narrow troughs and enigmatic double ridges, with a morphological sequence from simple struc-



FIGURE 5.2 Europa displays a wide variety of surface forms, including these so-called ridged plains. These features consist of many parallel, crosscutting ridges, often arranged in pairs. Dark material appears to be located primarily in the valleys between the ridges, suggesting that the dark material may be moving down the flanks of the ridges and collecting along their bases. This image shows a region some 20 km across and reveals features as small as 26 m. North is at the top, and the Sun illuminates the surface from the upper left. Courtesy of NASA/JPL.

tures to wider and more complex ones. The origin of these ridges is uncertain, but suggestions include diapiric intrusion, shear heating, diking, water-rich extrusion, and compression along preexisting tectonic structures. Wider pull-apart bands may represent complete separation of the icy lithosphere, in a manner broadly analogous to terrestrial seafloor spreading.

The global pattern of lineaments matches stress predictions if gravitational torques from Jupiter have induced nonsynchronous rotation of Europa's icy shell, implying decoupling of the surface from the interior, likely by a liquid-water ocean. Systematically varying stress directions and magnitudes induced by diurnal orbital flexing of Europa's icy shell can elegantly explain Europa's cycloidal-shaped ridge and fracture patterns and may drive strike-slip faulting along ridges and bands.^{20,21} Significant tidal amplitude is necessary to produce large diurnal stresses, and this argues strongly for a subsurface liquid layer^{22,23} but does not constrain its depth.²⁴ Large-scale folds have been recognized on Europa, but these can compensate for only a small fraction of Europa's ubiquitous extension.²⁵

Volcanism and Geysers

The discoveries of current eruptive activity on Io and Triton were highlights of the Voyager 1 and 2 missions.^{26,27} In the inner solar system, geologic activity is driven primarily by early accretion and differentiation and the slow decay of radioactive nuclides, with the result that continuing geologic activity was only expected on planets such as Earth and Venus with sufficient silicate mass. By analogy, no current geologic activity was expected on outer-planet satellites. This paradigm was altered by Voyager and by our new understanding of the effects of orbital evolution, tidal heating, and highly volatile crustal species.

Io has several hundred currently active, high-temperature silicate eruptions (Figure 5.3)²⁸ and a global average heat flow ~20 times greater than that of Earth.²⁹ Many of these lavas have extremely high temperatures and may be rich in Mg, similar to Archean komatiites and lunar mare basalts.³⁰ Voluminous flood volcanism, which has had pronounced effects on Earth's climate, is ongoing at Io. The high heat flow, Mg-rich and flood volcanism, and rapid tectonism, which we can directly observe on Io, provide insights into ancient processes on the terrestrial planets. In addition, the giant (up to 500 km) volcanic plumes of Io and the smaller geyserlike eruptions on Triton provide fundamental experiments in fluid dynamics.

Many other icy satellites exhibit evidence for past icy volcanism, expressed as smooth plains, ridges, lobate deposits, and mantling deposits.³¹ Active volcanism on some icy satellites is plausible today, based on the lightly cratered surfaces of Europa and Enceladus and models of atmospheric processes on Titan. Although Galileo yielded no evidence for active volcanism on Europa,³² continued searches are warranted.

Diapirism

Interior material also can be brought to the surface of a satellite through diapirism, in which buoyancy forces due to a density inversion cause mobile material to pierce and rise through a higher-density overburden.³³ On the icy satellites, Triton's pitted "cantaloupe" terrain offers the most dramatic example of a surface apparently turned inside out by diapirism, perhaps owing to compositional layering of various frozen volatiles. Triton's record of intense diapirism may reflect capture by Neptune and consequent tidal heating. Diapirism may also explain the unusual rounded "coronae" of Miranda—a satellite potentially frozen during the act of differentiation—perhaps induced by tidal heating.

Europa also may exhibit evidence of diapirism.³⁴ Pits, domes, and spots on Europa have been interpreted as the surface manifestations of thermally induced diapirism, where warm ice, probably in contact with a subsurface ocean, has risen through colder and denser ice above. Larger "chaos" regions on Europa consist of disrupted crustal blocks situated in a hummocky matrix (Figure 5.4). These also have been inferred to be the manifestation of diapirism and associated partial melting of the ice crust, though complete melting of a thin ice shell is an alternative hypothesis. Diapirs may be able to transport nutrients and/or organisms between the surface and subsurface ocean of Europa and other icy satellites.

Atmospheres, Surface Chemistry, and Interactions

The thin atmospheres and volcanism of Io and Triton serve to redistribute and modify volatile deposits on their surfaces. However, the Cassini-Huygens mission may reveal much more dramatic effects on Titan from an active "hydrologic" cycle associated with liquid hydrocarbons. The surface of Titan may be modified by methane and ethane rainfall and liquid hydrocarbon erosion, active ground-fluid processes, and littoral processes (Figure 5.5).

Titan

As does Earth, Titan has an atmosphere that is primarily nitrogen and a surface pressure of 1.5 bars. Titan's thermal profile indicates that methane (~10 percent abundance) and many minor organic constituents should exist in both liquid and gas phase and should rain out of the atmosphere, providing a liquid component to the surface.^{35,36} Titan's liquid cycle, with clouds, rain, and perhaps seas, may resemble our terrestrial counterpart, with several key



1 km (0.6 mile)

FIGURE 5.3 The margin of the lava flow field associated with the Prometheus volcanic plume on Jupiters' moon Io. This entire area is under Prometheus's active plume, which is constantly raining bright material onto the surface. The darkest regions, having margins similar to those formed by fluid lava flows on Earth, are believed to be relatively young because they are not yet covered with plume fallout and are, perhaps, too warm for bright gas rich in sulfur dioxide to condense. The older, brighter plains to the upper right are covered by ridges formed, possibly, by the folding of the surface or by deposition or erosion. The bright streaks emanating from the lava flow margins may arise where hot lava vaporizes sulfur dioxide. This image has a resolution of 12 m and was taken by the Galileo spacecraft on February 22, 2000. Courtesy of NASA/JPL.



FIGURE 5.4 This image from the Galileo spacecraft is a very high resolution view of the Conamara Chaos region of Jupiter's moon Europa. It shows an area where icy plates have been broken apart and moved around laterally in a hummocky matrix. Corrugated plateaus end in icy cliffs more than 100 m high; debris piled at the base of the cliffs can be resolved down to blocks the size of a house. The fracture running horizontally just above the bottom of the image is about the width of a freeway. Courtesy of NASA/JPL.

differences. Titan's main condensable is methane rather than water. Titan's atmosphere is more massive and cooler than that of Earth. Titan receives ~ 100 times less solar insolation, the energy that fuels terrestrial weather. In contrast, Titan has roughly 100 times more latent heat available for fueling weather than does Earth. Recent observations indicate the sparse presence of daily clouds that uniformly lie at the tropopause.³⁷ In addition, ground-based observations, recorded in the past two decades, show evidence for the unique occurrence of a hurricane-sized cloud system.³⁸ The formation mechanisms of clouds, the origin of the large and rare storm, and the effect of latent heat on cloud evolution and circulation are unknown, because only limited measurements of the lower atmosphere have been possible. Current and future investigations aim to understand Titan's coupled atmosphere and surface, which may provide analogs for processes important on Earth.

Improved understanding of Titan's evolution depends on knowledge of the depths and extent of its liquid reservoirs at and near the surface. The main atmospheric constituent, nitrogen, dissolves in methane. Therefore, the size and composition of the reservoirs reflect not only the total inventory of organics but also the amount of

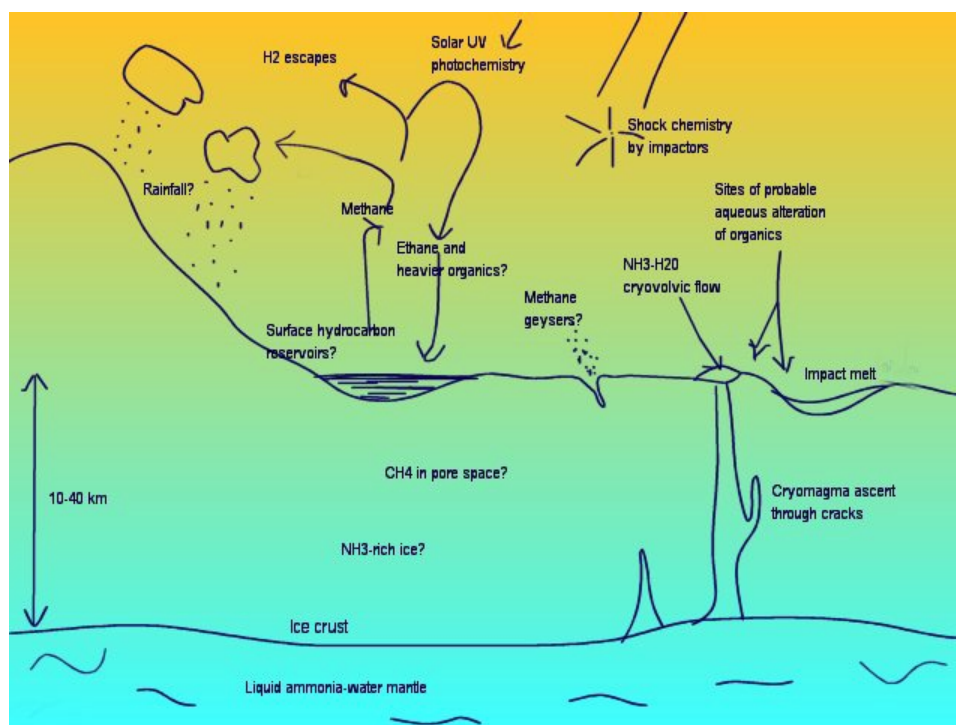


FIGURE 5.5 A schematic of the dominant processes affecting the volatile inventory on Titan and the formation of prebiotic molecules. Courtesy of Ralph Lorentz, University of Arizona.

nitrogen on Titan. The rapid and irreversible destruction of methane by solar ultraviolet photolysis indicates the need for a recent supply. Two extreme scenarios are possible: Current geologic activity may directly supply atmospheric methane (and lead to an atmosphere that varies in size with supply), or large near-surface reservoirs of methane, such as seas, may exist.^{39,40}

Organic chemistry on Titan occurs both in the stratosphere and on the surface. In Titan's stratosphere, the photolysis of methane coupled with electron dissociation of nitrogen instigates a rich organic chemistry, for which over a dozen organic species have been identified. The end-product of this chemistry, Titan's ubiquitous haze, consists of complex organic material with an elemental composition that has not yet been directly measured. Even the ratio of nitrogen to carbon in Titan's haze is unclear. Laboratory simulations of this satellite's photochemistry produce solid residues having optical properties similar to those of Titan's haze. Their elemental composition hints that alkanes, aromatic compounds, heteropolymers, and amino acids, key initial compounds in life's chemistry, are constituents of Titan's haze.⁴¹

Chemical reactions at Titan's surface proceed very slowly, potentially in cold (94 K) organic liquids. In this environment, organic chemistry evolves in a solvent over a long time period, well shielded from ultraviolet radiation, as on Earth. Yet Titan's atmosphere and surface are more reduced than Earth's (similar to Urey-Miller models of early Earth), conditions are cool, and the solvent is mainly hydrocarbon (methane and ethane). It is possible that the solids are not soluble in the surface liquids. At present, however, the composition of Titan's surface organics is poorly known and is inferred primarily from our understanding of the atmosphere. The path and extent of long-term organic evolution in a largely nonaqueous solvent are unknown. Titan provides us with a laboratory for this chemistry.

Titan has, on brief occasions, experienced chemical conditions more like those on Earth. Episodic heating, due to impacts and possibly volcanism, probably exposed organic material on Titan's surface to aqueous solutions. Liquid-water ponds ~0.5 km deep would survive on Titan's surface for as long as 1,000 years. Considerations of reaction rates relevant to these brief events indicate the ready production of compounds (such as purines, pyrimidines, aldehydes) important to prebiotic chemistry.⁴² At present, our understanding of organic chemistry is too poor to estimate how quickly life arose on Earth. Titan provides us with snapshots of this chemistry at 100- to 10,000-year intervals, longer than possible in laboratories and shorter than can be deciphered from our terrestrial record. Titan's natural laboratory may uniquely hold answers to the evolution of prebiotic chemistry on ancient Earth.

Triton

Four separate ices have been identified spectroscopically on Triton's surface: N₂, CH₄, CO, and CO₂.^{43,44} The latter three species (except perhaps CO₂) exist partially in solid solution with N₂, the main constituent. More complex organic molecules are also expected to be present as a result of photolysis and radiolysis. Triton's surface temperature of approximately 38 K creates an atmosphere in vapor pressure equilibrium with the ices, which is highly responsive to heating changes associated with solar insolation and the variable photometric and compositional properties of the surface. As a result, the atmosphere experiences large-scale sublimation, transport, and recondensation of N₂, CO, and CH₄. Another unique characteristic is Triton's geyserlike plumes that entrain dark dust and rise 8 km above the surface.⁴⁵ A diffuse haze pervades the atmosphere; it probably consists of the condensation of hydrocarbons created by photochemistry. Discrete clouds, likely condensed N₂, are present near the poles.

Io

Io's sulfur-rich chemistry reflects the moon's active volcanism.⁴⁶ Io's infrared spectrum is dominated by the signature of solid SO₂. The albedo, continuum spectrum, and atmospheric measurements indicate, however, that other sulfurous materials are present. The surface topography and hot-spot temperatures require the presence of silicates, which are largely covered by the sulfur-rich veneer.

Io's atmosphere is arguably the least understood in the solar system. It is uniquely affected by ubiquitous and time-variable volcanism, which adds to the atmospheric inventory through plumes and affects the surface temperature and composition. Ground-based spectroscopy identified the primary constituent, SO₂, and two of the minor components, SO and S₂.^{47,48} The surface pressure is around 1 nanobar and varies spatially by orders of magnitude. The vertical profile is poorly characterized. Two limiting, although related, origins are postulated: an atmosphere produced by sublimation of SO₂, and one produced by volcanic outgassing. The atmospheric structure is unclear and may be determined by several processes: hydrostatic equilibrium, plume dynamics, and general circulation driven by large pressure gradients. The roles of these processes are not well known and require knowledge of the surface properties (porosity, composition, and temperature), the atmospheric temperature and composition, atmospheric escape processes, and the composition and energetics of the plumes.

Icy Satellites

In addition to water ice, which by the 1970s had been identified on most of the icy satellites by ground-based spectroscopy, the surfaces of these bodies contain non-ice material, which may be composed of mixtures of silicates and carbonaceous material as well as components produced by charged-particle bombardment of their surfaces. Galileo's spectral measurements have also identified features due to CO₂, C-H, S-H, and C≡N on several of the Galilean satellites.⁴⁹ Similar materials have been identified in spectra of interstellar ice grains. This non-ice component presumably represents a mixture of material originally accreted with the satellites, subsequent comet and asteroid impacts, and components implanted and/or modified by magnetospheric environments. On Europa, the presence of heavily hydrated sulfates has been inferred, including sulfuric acid and sulfate salts. Charged-

particle irradiation of ice-rich surfaces can break molecular bonds, allowing recombination to form new compounds, as discussed below.

Iapetus is of special interest because the dark material on the leading hemisphere (albedo of 3 percent) is inferred to have an organic component. Its spectrum is consistent with a mixture of laboratory-synthesized organics (termed tholins), poly-HCN, and the Murchison organic residue.⁵⁰ The nature and origin of the dark material is unclear. The strong asymmetry with respect to the direction of orbital motion suggests some external control if not external origin.

Magnetospheric Processes and Interactions

Sputtering/Implantation

The large satellites of the gaseous giant planets spend all or most of their time in the corotating magnetospheres of these planets. The interaction of satellite and corotating plasma modifies the satellites' surfaces and atmospheres and leads to a net loss of volatile materials to the magnetospheres. At the present time, Io is known to lose more than a ton per second of volatile material (mostly S and O) to Jupiter's magnetosphere.⁵¹ Similarly, Europa is losing its icy surface at the rate of ~2 cm per million years (Myr) to Jupiter's magnetosphere.⁵² Ganymede's magnetic field partially shields the equatorial regions from plasma bombardment. However, it is estimated that the polar regions of Ganymede lose an average of 8 mm/Myr of ice from sputtering.⁵³ Callisto, in a more benign radiation environment, loses <0.4 mm/Myr of ice to sputtering. The plasma bombardment of icy surfaces results in the implantation of S derived from Io's torus into the crusts of icy satellites.⁵⁴ The irradiation of icy satellite surfaces also results in the production of H₂, O₂, H₂O₂, and other stable oxides that get embedded in the ices and also form tenuous atmospheres near the surface.⁵⁵ The irradiation of other ice contaminants such as C and S produces CO₂, SO₂, and H₂SO₄. The radiolysis of the surface by magnetospheric particles continuously cycles S between SO₂, H₂SO₄, and polymer S forms.⁵⁶ At Europa, the fast recycling of the crust (believed to occur over a time scale of 100,000 to 10 million years) may deliver oxidants from the surface to the subsurface ocean.⁵⁷ These oxidants could fuel life in the absence of sunlight.

Style of Plasma Interaction

The type and strength of satellite/magnetospheric interaction depends on the satellite's size, surface composition, and electrical conductivity, the presence or absence of an internal magnetic field in the satellite, and the density, composition, and speed of the interacting plasma. Based on these factors, three distinct types of interactions have been observed. In the nonconducting type of satellite/plasma interaction, as in the case of Callisto, the magnetospheric plasma slams into the satellite and is absorbed, but sputters some volatile material off the satellite's surface.

A second type of interaction, called the conducting-satellite/plasma interaction, is best illustrated by Io and Europa. Because of a well-developed ionosphere at Io and large plasma pickup near Europa, most of the magnetospheric plasma is diverted around the moons. Only a small fraction of the incoming plasma flux strikes the moons and sputters volatile materials off the surface. The strong Alfvén wing currents generated in the interaction are closed in the ionosphere of Jupiter where they generate visible footprints (see Figures 4.3 and 4.4).

The third type of interaction is epitomized by Ganymede, which generates its own internal magnetic field.⁵⁸ Ganymede's magnetic field is strong enough that it creates a minimagnetosphere of its own in Jupiter's magnetosphere, partially shielding the satellite from plasma bombardment. The interaction between Ganymede's magnetosphere and Jupiter's magnetosphere is similar to the interaction between Earth's magnetosphere and the solar wind, in which magnetic reconnection plays a key role.

Curiously, the other three Galilean satellites were found not to have internal fields at present. However, it is likely that some or all of the other large moons of the solar system were endowed with an internal magnetic field at some time in their evolution.

Induced Fields

Europa, Ganymede, and Callisto. Magnetic observations from the vicinities of Europa, Ganymede, and Callisto show that all three moons generate electromagnetic induction fields in response to the rotating field of Jupiter.^{59,60} The magnetic signatures are consistent with the presence of subsurface electrically conducting shells in these bodies. Detailed analyses for Europa and Callisto suggest that liquid subsurface oceans with thicknesses exceeding a few kilometers could account for the enhanced subsurface conductivities.⁶¹ Geological and geophysical lines of evidence are consistent with liquid subsurface oceans within Europa and Ganymede. However, the presence of electromagnetic induction from geologically inactive Callisto was indeed a surprise.

Titan. The only spacecraft to make in situ observation of the interaction of Titan with Saturn's magnetosphere was Voyager 1, which flew through the plasma wake of Titan. No appreciable internal magnetic field was observed (surface field strength <30 nT).⁶² The main pickup ion is N⁺, and the integrated surface pickup rate is ~10²⁴ ions per second. The geometry of the flyby was not suitable to infer the presence or absence of an electromagnetic induction signature, so magnetic measurements cannot yet speak to the question of an ocean within Titan.

SPACE MISSIONS FOR LARGE SATELLITE EXPLORATION

Spacecraft exploration represents the cutting edge of research in addressing the key scientific questions (see the section "Unifying Themes and Key Scientific Questions for Large Satellite Exploration," below) that are related to the theme of this chapter—"Active Worlds and Extreme Environments." The missions considered here range from currently launched and flying (Cassini) missions to those with extensive design already completed (Europa Geophysical Explorer, with significant heritage from Europa Orbiter), to future mission concepts with varying degrees of design and study (e.g., Titan Explorer, Europa Landers, Neptune Orbiter). Input on the characteristics and potential capabilities of these missions came from a variety of sources—project briefings, studies by NASA Centers, industry, NASA advisory committee studies and reports, and studies by National Research Council panels (particularly COMPLEX). In evaluating the potential of these missions for addressing key scientific questions, the Large Satellites Panel had to reach a common understanding regarding mission and experiment capabilities. Naturally, varying degrees of uncertainty occur in this process as one moves from well-understood missions and payloads to future candidates for which multiple mission options and possible payloads are still being vigorously discussed. The following is a brief description of the key elements that the panel considers to be related to each mission, largely on the basis of studies by the Jet Propulsion Laboratory. While details will change as these (and future) mission concepts evolve, the panel believes them to be representative of the types of missions and measurement capabilities available for the period under study.

Missions were considered within three broad cost categories: large, medium, and small. At present, experience indicates that the dollar cutoffs between these categories are about \$750 million and \$500 million, although cost estimates will change as the missions become better defined and as new technologies become practical. The nature of the large satellites considered in this panel's study and the missions required for major advances over current knowledge (developed primarily from flyby reconnaissance) dictate that many of the high-priority missions would be at least in the medium and most probably in the large category. The costs of high-energy launch vehicles, radioisotope power systems, long flight times, and radiation-hard electronics all contribute to this situation. Of particular concern is the fact that several of the panel's candidate missions are poorly studied to date. These missions are very challenging by the standards of inner planet missions and even past outer planetary reconnaissance. The panel urges more complete and competitive studies of these mission candidates for understanding their true costs and capabilities.

Large Missions

Cassini-Huygens

The Cassini mission with the Huygens Titan probe was launched in 1997. It will go into orbit around Saturn in July 2004 and will deploy the Huygens probe into Titan's atmosphere in January 2005. For its evaluation of Saturn satellite scientific issues, the panel assumed a successful primary Cassini mission and appropriate mission data analysis. A principal target of the mission is Titan. Huygens results, combined with Cassini's orbital remote sensing and in situ sampling of the upper atmosphere, should revolutionize our understanding of this satellite's atmosphere, its structure and composition, and the complex chemical processes occurring in it. Huygens descent data and mapping by several of Cassini's instruments (radar, imaging, and near-infrared spectroscopy) should provide a first close look at its haze-shrouded surface, identify landforms and possible regions of liquid hydrocarbon lakes or seas, and give an indication of the age and history of its surface. High-precision gravitational measurements will place constraints on its internal structure and history, and may be able to determine if there exists a subsurface liquid-water-rich layer in this satellite. Studies of the other satellites in the system will also be important, providing information on the history and evolution of the satellite system, the interactions of the satellites with Saturn's magnetospheric environment, and the origin of the dark, presumably organic-rich material on the enigmatic satellite Iapetus.

Europa Geophysical Explorer

The Europa Geophysical Explorer mission is designed to follow up and significantly expand upon the remarkable discoveries made by the Galileo mission, suggesting that Europa may have a global liquid-water ocean beneath an ice crust that may be only a few kilometers to tens of kilometers thick. The primary objectives of the mission, as defined by the Europa Orbiter Science Definition Team, can be split into two groups in terms of their priority. The highest-priority, or Group 1, objectives are as follows:

- Determine the presence or absence of an ocean;
- Characterize the three-dimensional distribution of any subsurface liquid water and its overlying ice layer;
- Understand the formation of surface features, including sites of recent or current activity; and
- Identify candidate landing sites for future lander missions.

The lower-priority, or Group 2, objectives are the following:

- Characterize the surface composition, especially compounds of interest to prebiotic chemistry;
- Map the distribution of important constituents on the surface; and
- Characterize the radiation environment in order to reduce the uncertainty for future missions, especially landers.

Complementary discussions of Europa objectives are contained in COMPLEX's 1999 report, *A Science Strategy for the Exploration of Europa*.⁶³ For the present study, the panel has assumed the basic capabilities and "strawman" payload described in the 1999 Europa Orbiter Announcement of Opportunity:⁶⁴ at least a 30-day mission in orbit, detailed gravity and altimetry measurements of the tides (with ~1-m accuracy), ice-penetrating radar, and an integrated camera/remote-sensing package. The panel also assumes (and recommends) some augmentation to this payload, including a magnetometer and some surface compositional experiment(s) capable of meeting the Group 2 objectives. In addition, the panel assumes that some significant data will be returned during the Jupiter orbital tour phase of the mission from multiple Europa, Ganymede, and Callisto flybys and from more distant observations of Io.

Europa Pathfinder Lander

The panel considered two levels of potential landed science at Europa. The Europa Pathfinder concept involves a small (~10- to 20-kg) payload delivered to the surface from an orbiting spacecraft using a retro-propulsion system and airbags to achieve landing. Total system mass is in the vicinity of ~200 kg, including the retro-propulsion and airbag landing systems. A key feature of the mission studied to date is a compact lander body capable of operating from an arbitrary landed attitude.

Proposed instrumentation could include a sophisticated geophysical station with seismic/acoustic sensors, a magnetometer, and possibly a tilt meter, combined with surface elemental and phase composition measurements of the immediate vicinity of the lander using some combination of optical, infrared, Raman spectrometer, and Laser Induced Breakdown Spectroscopy (LIBS) techniques. No subsurface sampling, sample handling, or preparation systems are envisioned for the Europa Pathfinder. In addition to data relayed from the lander to the orbiter, complementary orbital science is assumed, with the details to be determined by results of the Europa Geophysical Explorer mission. Technology needs include airbag and landing systems for the Europa environment.

Europa Astrobiology Lander

A more ambitious Europa mission concept involves a study of organic chemistry and possible biosignatures from a landed station. The science rationale and some of the experiment concepts for such a mission have developed recently in a series of workshops sponsored by the Europa Focus Group of the NASA Astrobiology Institute, and are complementary to objectives developed by the 1999 NASA Campaign Science Working Group for Prebiotic Chemistry in the Outer Solar System, but no complete system/mission studies of the concept have been performed.

The key elements that distinguish this candidate mission (which could also carry some of the same payload as that on the Europa Pathfinder Lander) are the inclusion of subsurface sampling capability to obtain material that is less processed by radiation (at depths greater than approximately 10 cm) and sample handling and sample preparation for a sophisticated chemical analysis suite, including a gas chromatograph/mass spectrometer and the coring instrument. This greatly extends the compositional capability, and particularly the characterization of organic materials, from that envisioned for the Europa Pathfinder, but with a significant increase in complexity and cost (unquantified at present).

As does the Pathfinder, this concept assumes either prior Europa Geophysical Explorer data for global context and/or orbital science on its own supporting orbiter delivery spacecraft. In addition to radiation-hard electronics, this class of mission requires significant technology development in the experimental areas of highly compact and sophisticated chemical analysis systems.

Titan Explorer

It is expected that Cassini-Huygens results will set the agenda for the future exploration of Titan. However, a number of studies of mission concepts that would form the basis for future exploration of Titan's atmosphere and surface have already been discussed. These are based on anticipation of what Cassini-Huygens will accomplish and also on its known limitations. On the basis of these studies, the panel assumed a generic Titan Explorer that would be capable of addressing many key questions in the relevant areas. The mission assumes the use of aerocapture at Titan to deliver an orbiter and an atmospheric "aerobot."

The key elements of the proposed exploration are mobility within the atmosphere so that different levels, weather, and processes can be studied in detail with in situ experimentation, including aerosol collectors, mass spectrometers, and other atmospheric structure and composition instrumentation. In addition, the system is assumed to be capable of making high-resolution remote observations of the surface from various altitudes and of descending to the surface multiple times during the mission to make close-range and possibly in situ measurements of surface composition and properties. Although landed packages delivered by the atmospheric vehicle have also been discussed in various combinations with the atmospheric experimentation, the panel assumes the simpler

(single aerobot with surface landing capability) for its evaluation at this time. The orbiter is assumed to have limited communications and some science capability, perhaps focused on global context for the Titan Explorer data and studies of the stratospheric regions not reached by the aerobot.

Technology-development needs include a range of technologies for the aerobot (or other forms of atmospheric mobility), as well as advanced radioisotope power sources for long-life operations.

Uranus Orbiter

An orbiter mission to Uranus is assumed to be able to address key satellite objectives through repeated flybys of the five major satellites in the system. Geological, geophysical, and geochemical characterization of the satellites should be equivalent to that achieved for the Galilean satellites by Galileo and anticipated for the Saturn system from Cassini-Huygens. A suite of remote-sensing camera/spectrometer systems and space physics instrumentation for studying magnetosphere-satellite interactions is assumed.

Neptune Orbiter

The Neptune Orbiter mission was of particular interest to this panel because of the opportunity to study Triton, a world known to have intriguing volcanic and atmospheric activity despite its low surface temperatures. For its purposes, the panel assumes that such a mission would include repeated flybys of Triton with an instrument suite equivalent to that of the Galileo or Cassini orbiter systems. As noted below, this mission is only feasible using advanced technology for solar electric propulsion combined with advanced aerocapture or nuclear-electric propulsion to achieve orbit with an acceptable payload/flight-time combination.

Medium Missions

Io Observer

The mission concept for Io involves either a Jupiter orbiter dedicated to multiple close flybys of Io or a multirole mission, with part of the mission and payload being devoted to magnetospheric space physics goals and/or atmospheric and auroral observations. The assumption that this mission could achieve the stated goals within this cost category rests partially on assuming that heritage from the Europa Geophysical Explorer would allow significantly reduced costs. A suite of remote-sensing experiments is assumed, with emphasis on the monitoring of Io's active volcanism and related processes.

Ganymede Orbiter

The Ganymede Orbiter mission is similar in concept to the Europa Geophysical Explorer, but the impracticable goal of measuring Ganymede's very small tides is replaced by an increased emphasis on Ganymede's internally generated magnetic field and its interaction with that of Jupiter. No detailed studies are yet available, and the assumption that this mission could achieve the stated goals within this cost category rests partially on assuming that the lesser radiation environment and heritage from the Europa Geophysical Explorer mission would allow significantly reduced costs.

Neptune Flyby

The Neptune Flyby mission concept would be similar to the Kuiper Belt-Pluto Explorer discussed in Chapter 1, but with a considerably expanded payload to achieve multiple objectives for Neptune, the ring system, the magnetosphere, and Triton. The panel assumes that modern instrumentation designed for the study of Triton based on current knowledge from the Voyager flyby in 1989 could make a major advance over our current knowledge of Triton. The major limitation for observations of such an active world is that it obviously would provide only a

brief snapshot of the Neptune system, and cannot definitely determine the presence or absence of a subsurface water layer via variations in the induced magnetic signature.

Small Missions

For the reasons discussed earlier, dedicated missions to achieve major results in large satellite science rarely fit realistically in the small category. Other types of science investments requiring resources in the range of those required by Discovery-class missions or below can, however, make major contributions to large satellite science, although they are not, strictly speaking, new missions. Examples include the following:

- *Extended/enhanced missions, for example, a Cassini extension.* Once the investment in a major mission is made, it is frequently possible to derive very high science benefit from extending the lifetime and/or objectives where other resources permit. Past examples include the Voyager Uranus and Neptune missions, Galileo's extended exploration of Europa and Io, and the addition of asteroid encounters to Galileo's mission and a Jupiter encounter for Cassini. A near-term opportunity is the likely extension of the Cassini orbital mission beyond the nominal 4-year prime mission. Detailed planning for an extended mission has not yet been undertaken, but several possible scenarios could result in major new Titan and/or icy satellite results for costs equivalent to, or less than, those for a single low-cost mission.
- *Ground- and space-based telescopes.* The use of telescopic observations of all sorts has been of tremendous importance to solar system science and to satellite studies in particular. Investments in the continuing use and upgrading of current facilities and instrumentation, as well as the development of new systems, are vital parts of a balanced strategic program. (See the more detailed discussion in the following subsection.)

Key Enabling Technologies for Large Satellite Exploration

New technologies create opportunities for enhancing and/or enabling missions by a combination of increasing capabilities, decreasing resource use (mass, power, volume, and so on), and lower cost. Many of the key technologies are related to all or most of the missions considered in this section. These include the following:

- *Telemetry.* Maintenance of essential Deep Space Network capabilities is crucial to all future missions. In the period of time considered by this survey, significant improvements in systemwide telemetry capability are expected to be needed in order to handle the data requirements from increasingly sophisticated instrumentation and the large number of potential deep-space missions. This is particularly true for missions related to large satellite objectives, owing to their location in the outer solar system and to the time-criticality of some mission phases.
- *Power systems.* All past and current missions targeting the large satellites of the outer solar system have relied on radioisotope power systems because of the large heliocentric distances, long flight times, and requirements for reliability and radiation tolerance involved. Maintenance of this capability is critical for most if not all of the outer solar system missions considered in this study. Additional improvements in efficiency and design of these systems are highly desirable for the more ambitious missions involving landed packages and surface or atmospheric mobility.
- *Radiation-hard electronics, shielding, reliability and fault tolerance.* All outer solar system missions involve, to some degree, long lifetimes, high reliability, and tolerance to reasonably large total radiation exposure from solar, galactic, and planetary magnetospheric sources. Many of the highest-priority large satellites (e.g., Europa and Io) reside in extremely high radiation environments. Improvements in radiation-hard components and design are essential to future exploration of these worlds.
- *Microelectronics/autonomy.* More capability in smaller packages is a key component in achieving difficult science goals within mass, dollar, and power constraints. Hardware and software advances in this area, coupled with the radiation tolerance and reliability requirements noted above, are critical for making future missions capable of reaching their science goals.

- *Propulsion.* Outer-planet missions in general, and particularly missions to satellites residing deep in the gravity wells of large planets, are severely limited by the physics of propulsion—the rocket equation—which dictates very small payload mass fractions compared with propulsion mass for current chemical systems. Technology development in the area of electric propulsion is one important component in improving this situation in the future.⁶⁵ Unfortunately, current solar-electric and future nuclear-electric technologies do not offer large benefits for the mission types considered here, except for Neptune Orbiter. Nuclear-electric systems could potentially yield huge improvements in payload mass and capability for more distant, future missions with large energy requirements.

- *Aerocapture.* The use of a planet's or satellite's atmosphere to slow an approaching spacecraft is another approach to solving the low-payload-mass problems noted above. The precursor technology of aerobraking has already been demonstrated at Venus and Mars. Further research into materials, structures, and techniques required for full aerocapture are necessary in order for future missions to take advantage of this technique. Titan orbiters and atmospheric explorers are one highly promising use of this technology. One of the potential missions of great interest for both large satellite and giant planet research—the Neptune Orbiter—requires either solar-electric propulsion combined with advanced aerocapture capability or nuclear-electric propulsion to achieve an acceptable payload and mission capability.

- *Planetary protection.* Many of the satellites in this study are potentially interesting for the study of organic chemistry, prebiotic chemistry, and environments of biological interest. Examples include organic-rich Titan and satellites that may have liquid subsurface oceans. Exploring these environments while maintaining an acceptably low risk of contaminating them with terrestrial organisms poses new challenges. Improvements and research in techniques of planetary protection are needed to address these issues for future missions.

Supporting Research for Large Satellite Exploration

Many previous NRC and NASA advisory reports have stressed the importance of both adequate resources for mission data analysis and a strong, ongoing research and analysis program in solar system science. It is particularly important to emphasize these areas in a strategic study such as this, because their relationship to what is usually seen as the major science activity of NASA—that is, flying missions—is complex and frequently misunderstood. Research related to solar system exploration in the current era is unusual in that it is funded almost entirely by only one office within one federal agency (NASA). Other disciplines in physics, astronomy, and the geosciences typically are supported by programs in multiple agencies and offices, university programs, industrial research, and even state-sponsored research programs.

The idealized, academic view of NASA's relationship to the solar system research community is that NASA flies the missions that the researchers say are most important and then supplies the data to the community, which proceeds to go about the business of “doing science” with it. In reality, mission and research activities are so closely coupled within NASA that the very research designed to utilize data from past missions and develop the scientific basis and instrumentation for future missions is often in direct competition for scarce resources with the missions themselves. These areas must be given equal weighting with individual missions to arrive at a strong program of solar system exploration.

The panel considers four closely connected types of research:

- Mission data analysis,
- Research and analysis,
- Laboratory studies, and
- Earth-based astronomy.

Mission Data Analysis

Each mission has a core group of researchers involved directly with the mission and its experiments. In addition, there is always a wider group of scientists with particular interests in the mission's objectives who

independently participate in the analysis of mission data at various levels. Typically, mission data-analysis programs fund the acquisition and initial analysis of mission data during the mission's active phase and for some years afterward, frequently with a broadened pool of research proposals. The split between what are regarded as direct project costs and costs that are part of the broader R&A budget has varied from mission to mission over time.

Research and Analysis

As noted above, R&A is not always cleanly separable from data analysis, but generally is the program area that funds researchers to perform what is frequently referred to as "basic research" in the field. This includes theoretical, observational, and experimental studies and the analysis of data from many sources, not just one mission.

Laboratory Studies

Laboratory studies are, of course, one aspect of R&A, but historically they have been viewed separately, because support commonly requires substantial investment in acquiring and maintaining relatively large-scale and costly equipment.

Earth-Based Astronomy

Ground- and space-based telescopic studies have been important to the development of our understanding of large satellites dating back to the discovery of Jupiter's moons by Galileo Galilei and Simon Marius in 1610 and continuing to the present day with observations of Io's volcanoes, Titan's surface, and spectroscopy of many satellites. These observations and many more provide the basis for formulating the planetary exploration missions, instrumentation, and experiments that have led to our current state of knowledge. Telescopic observations also play a vital role in supporting and extending the results from missions, commonly changing our way of analyzing these results or prompting further investigations, often while the mission is still active. Capabilities from the ground and from Earth orbit strongly complement those of missions by uniquely enabling the following:

- Long-term studies of, for example, the seasonal response of Titan's and Triton's atmospheres and the rapid evolution of Io's surface;
- Investigations of rare events, such as major volcanic eruptions on Io and large cloud systems, or "storms," on Titan;
- Measurements with instruments that are not yet feasible for spacecraft observations, and the development of new techniques and instrumentation for future space applications;
- Continual studies of satellites before and after space missions that frame questions and provide temporal context; and
- Technical support for the success of spacecraft missions, such as the ongoing determination of wind fields on Titan, needed to track the Huygens probe.

At present, planetary astronomy is supported primarily through NASA's Infrared Telescope Facility, a 3-m telescope on Mauna Kea, for which half the time is allotted to planetary investigations. In addition, limited observing opportunities exist on the Hubble Space Telescope and large ground-based systems (such as the Keck telescopes). The IRTF plays a key role in planetary research, with state-of-the-art infrared instruments, quick response to time-critical events, and a scheduling facility that allows the investigation of long-term planetary phenomena. Continued maintenance and upgrading of these facilities are essential for future planetary satellite research.

Mission development and scientific return and fundamental research also require state-of-the-art capabilities from the ground, such as the proposed Giant Segmented Mirror Telescope (GSMT), and the James Webb Space Telescope (JWST) in Earth orbit. The advantage of a GSMT, with an accompanying advance in adaptive optics,

is the increased spatial resolution and sensitivity to faint sources. A GSMT can address questions such as the weather on Titan, the vertical structure of Io's atmosphere and its temporal evolution, volcanic activity and surface changes on Io, and the seasonal wind field on Titan. To address these and other topics, planetary astronomy must play an active role in the scientific strategies for the proposed large-aperture systems.

UNIFYING THEMES AND KEY SCIENTIFIC QUESTIONS FOR LARGE SATELLITE EXPLORATION

The Large Satellites Panel evaluated and organized key scientific questions around four major themes that, in its opinion, best capture the most important scientific questions pertinent to large satellites. They are as follows:

- *Origin and evolution of satellite systems.* Tidal heating and orbital evolution have led to complex histories for some large satellites. Satellite systems may form and evolve in ways analogous to planetary systems but are much more accessible for detailed study than are extrasolar planetary systems.
- *Origin and evolution of water-rich environments in icy satellites.* Evidence for water within the icy Galilean satellites has led to a new paradigm for the potential habitability of planetary systems. Europa offers the greatest potential for finding life, because the subsurface water may interact with the surface and the silicate mantle.
- *Exploring organic-rich environments.* Although organic materials are common in the solar system, only Earth and Titan allow the study of organic chemistry in the presence of a thick atmosphere, a solvent, and a solid surface. Titan may enable study of the conditions leading to the origin of life.
- *Understanding dynamic planetary processes.* We can best understand physical processes by observing them in action, and satellites such as Io, Titan, and Triton offer a broad range of current activity, from the interiors to the surfaces, atmospheres, and magnetospheres.

Origin and Evolution of Satellite Systems

The satellite systems around the giant planets were formed by processes reasonably analogous to those that formed the solar system. The proximity of these satellite systems (as opposed to extrasolar planetary systems) allows detailed study of the results of four different accretional "experiments." The extrasolar planetary systems observed to date tend to contain giant planets, and the apparent rarity of terrestrial planets within a few astronomical units of the central star makes understanding the origin and evolution of satellite systems a step toward understanding the origin and evolution of extrasolar planetary systems. Study of the jovian system has revealed the importance of resonant orbital interactions in the evolution of satellite systems. Io demonstrates the importance of tidal heating in providing an energy source for internal dynamics, while Europa may provide an example of a habitat that depends on this energy, an idea that has considerably broadened our concept of habitable worlds. Exploration of the outer-planet satellites contributes to our understanding of how the orbital and thermal evolution (coupled through tidal interactions) of satellites and satellite systems leads to the development of habitable environments. The following key questions emerge as the most important next steps toward understanding the origin and evolution of satellite systems:

- How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?
- How do factors such as size, composition, orbital evolution, and tidal heating influence the differentiation and outgassing processes in large and midsized satellites? In particular, why is Titan the only large satellite with a thick atmosphere?
- To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
- How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?
- What does the magnetic field of Ganymede tell us about its thermal evolution, and do other large satellites have intrinsic magnetic fields?

Origin and Evolution of Water-Rich Environments in Icy Satellites

Perhaps the most significant question that humankind can ask and effectively address about the universe around us is, Are we alone? In the coming decade and continuing into the decade beyond, solar system exploration has the opportunity to make significant advances toward answering the question of whether life does or can exist beyond Earth in the solar system. Based on Galileo results, a new paradigm has emerged in which many, if not most, large icy satellites that circle cold gas giant planets in the solar system and other planetary systems contain liquid-water oceans. This paradigm shift implies that the habitability zone around our star and other stars is extended to include circumplanetary belts surrounding Jupiter-sized planets. Four top-level questions emerge:

- Can and does life exist in the internal ocean of an icy satellite?
- What combination of size, energy sources, composition, and history produce long-lived internal oceans?
- What is the distribution of internal water, in space and time?
- What is the chemical composition of the water-rich phase, and does surface chemistry reflect interior ocean composition?

Exploring Organic-Rich Environments

Titan's wealth of organic material and its possible seas uniquely resemble those of Earth. Titan illuminates the organic chemistry that proceeds in more reduced environments than Earth's. It is an intact chemical laboratory where ultraviolet photolysis and electron bombardment initiate the synthesis of carbon and nitrogen that ultimately forms complex organic solids in the stratosphere. Less well understood is the long evolution of chemistry at Titan's surface, where both organic liquid and solid precipitates are predicted. In addition, Titan is believed to support a liquid cycle involving atmospheric methane vapor and surface liquids. As such, clouds form over bodies of liquid, rain occurs, and the circulation responds to the release of latent heat, as on Earth. Yet, on Titan the energetics driving these events differs from the terrestrial experience. Titan provides us with a new perspective on weather processes inherent to our home planet. Most important, it serves as a natural laboratory in which complex prebiotic chemistry may have evolved. The following top-level questions emerge:

- What are the chemistry, distribution, and cycling of organic materials on Titan?
- Is Titan internally active, producing water-rich environments with potential habitability?
- What are the current state and the history of Titan's surface?
- What drives the meteorology of Titan?
- Has there been climate change on Titan?
- Could Titan support life forms that do not require liquid water?

Understanding Dynamic Planetary Processes

The outer-planet satellites are natural laboratories for a diverse range of physical and chemical processes of great interest to scientists and those who value science. These processes cannot be studied in small artificial laboratories, and some of them, such as active flood volcanism, cannot be studied in nature on our own planet. Io is the most extreme example of an active world that includes vigorous mantle convection, volcanism, tectonism, atmospheric loss, and magnetospheric interactions. Cracking, faulting, and diapirism in Europa's ice shell are probably still active. Ganymede has an active core and magnetosphere. Titan has active meteorology, atmospheric chemistry, and perhaps active "fluvial" and volcanic processes. Enceladus must somehow have supplied the E ring of Saturn. Triton has active geysers and perhaps active glaciers and diapirism. Magnetospheric sputtering and implantation modify many satellite surfaces. Perhaps the best way to illustrate the rich science potential is to list the relevant key questions in three categories:

- *What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?* Specifically: What is the nature and history of Ganymede's active core? Does Io have

a magma ocean? Are there active magmatic processes in Europa's silicate core? Do Titan, Triton, Enceladus, or other satellites have active interiors?

- *What are the currently active endogenic geologic processes (volcanism, tectonism, and diapirism) and what can we learn about such processes in general from these active worlds?* Specifically: What can Io's high heat flow, ultramafic lavas, large-scale eruptions, and tectonics tell us about ancient geologic processes on the terrestrial planets? How active is the fracturing, faulting, and diapirism in Europa's ice shell, and how often does liquid water reach the surface? Are there active volcanic or tectonic processes on Titan? What drives the geysers on Triton: solar or internal energy?

- *What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?* Specifically: How can the dynamics of plumes on Io and Triton be explained? Do any other satellites have active venting? What can be learned about planetary meteorology from Titan? How active is Titan's "hydrologic" cycle, and how does it modify the surface? Can Io-like magnetospheric interactions enable discovery of large satellites around extrasolar jovian planets? How do satellites lose volatiles and atmospheres?

Key Measurement Objectives for Exploring Large Satellites

Table 5.2 summarizes this panel's effort to quantify measurement objectives and rate the capabilities of current and future missions in meeting those objectives. For each key scientific question, the panel identifies several critical measurement objectives. Because a measurement objective may be met by using several different techniques, the suite of instruments that should be included in the payload of each of the missions is not explicitly identified. If a measurement objective is not applicable or is unachievable by a mission, this is designated by "—". However, if a significant advance in understanding of that measurement objective would occur from a mission, the mission is assigned a single "x." Major advances are signified by "xx," and any expected breakthroughs in understanding are indicated by "xxx."

Through this approach, missions to Europa and Titan stand out as the highest priority. This analysis also illustrates that a flyby-type mission such as the Neptune Flyby fares poorly in the rating matrix because many important measurement objectives can only be met from the global and/or temporal coverage provided by an orbiting spacecraft or from in situ surface measurements from a lander. It should be noted that the Uranus Orbiter also fares poorly compared with the Neptune Orbiter, because dynamic Triton is especially interesting. These results are incorporated into Table 5.3 in the section below, together with a discussion of mission targets.

RECOMMENDATIONS OF THE LARGE SATELLITES PANEL TO THE STEERING GROUP

Rationale for Recommendations

As detailed above (see Table 5.2), there are several key questions answers to which would lead to major scientific advances or breakthroughs in characterizing the outer solar system's large satellites. However, spacecraft missions and other initiatives with costs approaching a billion dollars must do more than advance scientific disciplines. They must address the most basic questions of importance to all of humanity, such as the questions that motivate this survey: Are we alone? Where did we come from? What is our destiny? The Large Satellites Panel has identified four relevant, high-priority questions that can be addressed through the continued study of large satellites. They are as follows:

1. Is there extant life in the outer solar system?
2. How far toward life does organic chemistry proceed in extreme environments?
3. How common are liquid-water layers within icy satellites?
4. How does tidal heating affect the evolution of worlds?

B. Origin and Evolution of Water-Rich Environments in Icy Satellites

1. What is the chemical composition of the water-rich phase?	Remote and in situ composition observations	XX	XXX	XXX	XX	XXX	X	XX	X	XX	XX	X	X
2. What is the distribution of internal water, in space and in time?	Geology/stratigraphy	XX	XX	XX	XX	XX	—	XX	X	XX	XX	—	X
	Subsurface sounding	X	X	XXX	XXX	XXX	—	XX	—	XX	X	—	X
	Internal structure	XX	XX	XX	XXX	XXX	—	XX	—	XX	XX	—	—
	Elemental and isotopic composition	XX	XX	—	XX	XXX	X	X	—	X	X	X	—
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?	Heat flow	—	—	—	—	XX	XX	—	—	X	—	—	—
	Geology	XX	X	X	X	—	—	X	X	X	—	—	—
	Secular variation of orbital parameters	—	—	—	—	XX	—	—	—	—	XX	—	—
	Composition	X	XX	XX	XX	XXX	—	XX	X	XX	XX	X	X
	Internal structure	X	XX	XX	XXX	XXX	—	XX	X	XX	X	—	—
	Intrinsic magnetic field (past/present)	XX	XX	XX	XX	XX	—	XXX	—	XX	XX	—	—
4. Can and does life exist in the internal ocean of an icy satellite?	Search for evidence of biology and organic compounds at surface and in the deeper interior	X	XXX	XX	XX	XXX	—	X	X	X	X	X	X
	Sample water layers	—	—	—	—	—	—	—	—	—	—	—	—
	Characterization of surface radiation environment	X	XX	XX	XX	XX	X	XX	X	XX	X	—	—
	Characterization of chemistry of surface and ocean	X	XX	XX	XX	XXX	—	XX	X	XX	X	X	—
	Life in extreme environments (Earth analogues)	—	—	—	—	—	—	—	—	—	—	—	XXX
	Transport processes	X	XX	XXX	XX	XX	X	XX	X	XX	XX	—	—

C. Exploring Organic-Rich Environments

1. What is the nature of organics on large satellites?	Composition (elemental, isotopic, and molecular), remote and in situ	XXX	XXX	X	XX	XXX	X	XX	XX	XXX	XX	XXX	—
	Production/loss (radiation, degassing, escape, lightning, and exogenic/endogenic)	XXX	XXX	X	XX	XXX	X	X	XX	XXX	X	X	X
	Physical state	XXX	XXX	X	XX	XX	X	X	XX	XX	X	X	XX
	Optical properties	XX	XX	X	X	X	X	X	X	X	X	X	XXX
	Reaction rates/kinetic information	XXX	XX	X	X	X	X	X	X	X	X	—	XXX
2. What are the processes currently affecting organic-rich surfaces?	Fluvial processes	XXX	XXX	—	—	X	—	—	—	—	—	—	—
	Impact processes	XXX	XX	XX	—	X	—	X	X	XX	X	X	X
	Cryovolcanic processes	XXX	XXX	XX	XX	XX	X	—	XX	XXX	X	X	X
	Tectonic processes	XX	XX	X	XX	XX	X	X	X	XX	X	—	—
	Aeolian processes	XX	XX	—	—	—	—	—	X	XXX	—	—	—
	Chemical (and radiation) processes	XX	XXX	X	XX	XX	—	X	X	X	X	XX	XX

TABLE 5.2 Continued

Scientific Themes/ Key Questions	Measurement Objectives										
C. Exploring Organic-Rich Environments (<i>continued</i>)											
3. How does organic chemistry evolve in a hydrocarbon solvent?	Cassini-Huygens	Titan Explorer	—	—	—	—	—	—	—	—	—
		Europa Geophysical Explorer	—	—	—	—	—	—	—	—	—
		Europa Pathfinder Lander	—	—	—	—	—	—	—	—	—
		Europa Astrobiology Lander	—	—	—	—	—	—	—	—	—
4. How do atmospheric processes affect organic chemistry?	Cassini-Huygens	Titan Explorer	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
		Europa Geophysical Explorer	—	—	—	—	—	—	—	—	—
		Europa Pathfinder Lander	—	—	—	—	—	—	—	—	—
		Europa Astrobiology Lander	—	—	—	—	—	—	—	—	—
D. Understanding Dynamic Planetary Processes	Cassini-Huygens	Titan Explorer	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
		Europa Geophysical Explorer	—	—	—	—	—	—	—	—	—
		Europa Pathfinder Lander	—	—	—	—	—	—	—	—	—
		Europa Astrobiology Lander	—	—	—	—	—	—	—	—	—
1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?	Cassini-Huygens	Titan Explorer	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
		Europa Geophysical Explorer	—	—	—	—	—	—	—	—	—
		Europa Pathfinder Lander	—	—	—	—	—	—	—	—	—
		Europa Astrobiology Lander	—	—	—	—	—	—	—	—	—

2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?	Observations of dynamic processes with high spatial and temporal resolution	x	xx	xx	xx	xx	xxx	x	xxx	x	—	—
	Composition of recent surface deposits, plumes or geysers, and atmospheres	x	xxx	x	xx	xx	xx	x	xx	x	xx	x
	Seismic or acoustic observations	—	—	—	xxx	xxx	—	—	—	—	—	x
	Search and discovery of new types of activity	xx	xxx	xxx	xx	xx	xxx	x	xx	xxx	x	—
3. What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?	Dynamics of plumes, geysers, atmospheres, exospheres, and magnetospheres	xx	xxx	xx	x	x	xxx	x	xx	xxx	x	x
	History of volatiles	x	xxx	xx	xx	xxx	xxx	x	xx	xxx	x	x
	Atmospheric loss (fields and particles)	xx	xx	xx	x	x	xxx	xxx	x	xxx	x	—

NOTE: xxx = breakthrough, xx = major advance, x = significant advance in understanding, — = not applicable.

The first question directly addresses the major exploration theme “Are we alone?,” and the second question directly addresses the theme “Where did we come from?” The third and fourth questions address habitability, in this and other planetary systems, which is relevant to all three overriding themes, including “What is our destiny?”

Mission Targets

What is the best strategy to address these questions? Europa and Titan stand out as the highest-priority targets. Each is the key to one of the high-priority questions listed above, and each addresses one major exploration theme and is important for others (Table 5.3).

Europa is the satellite that holds the most promise for understanding the potential habitability of icy satellites. Convincing evidence exists for the presence of water within just a few to tens of kilometers from the surface, and there is evidence for the recent or ongoing transfer of material between the surface and the water layer. Europa’s ocean is probably in direct contact with a rocky mantle below and so potentially with hydrothermal systems, and surface and intra-ice oxidants transported to the ocean may be able to nourish oceanic organisms. The first step in understanding the potential for icy satellites as abodes for life in the universe is to send a spacecraft to Europa, in order to confirm the presence of an interior ocean, to characterize the satellite’s ice shell, and to understand its geological history. Europa is also key to addressing high-priority questions 3 and 4, above. It is the best target for theme B—origin and evolution of water-rich environments in icy satellites—and is important to themes A (see Table 5.3) and possibly themes C and D. Given the high cost of the Europa Geophysical Explorer, the panel

TABLE 5.3 Targets and Missions for Future Exploration

	Best Targets	Missions
Theme		
A. Origin and evolution of satellite systems	Satellite systems	Cassini-Huygens, Europa Geophysical Explorer, Neptune Orbiter, Uranus Orbiter
B. Origin and evolution of water-rich environments in icy satellites	Europa	Europa Geophysical Explorer, Europa Pathfinder Lander, Europa Astrobiology Lander
C. Exploring organic-rich environments	Titan	Cassini-Huygens, Titan Explorer
D. Understanding dynamic planetary processes	Io, Titan, Triton	Cassini-Huygens, Io Observer, Titan Explorer, Neptune Orbiter
High-Priority Questions		
1. Is there extant life in the outer solar system?	Europa	Europa Astrobiology Lander
2. How far toward life does organic chemistry proceed in extreme environments?	Titan	Titan Explorer
3. How common are liquid-water layers within icy satellites?	Triton, Titan, Enceladus, Callisto, Ganymede, Europa	Cassini-Huygens, Europa Geophysical Explorer, Neptune Orbiter, Ganymede Orbiter
4. How does tidal heating affect the evolution of worlds?	Io, Europa, Ganymede, Triton, Enceladus, Miranda	Io Observer, Europa Geophysical Explorer, Neptune Orbiter, Ganymede Orbiter, Cassini-Huygens, Uranus Orbiter

considers it essential that the mission address both the Group 1 and Group 2 science objectives described by the Europa Orbiter Science Definition Team and that it contribute to Jupiter system science (theme A) during the ~2-year Galileo-like tour prior to capture into Europa's orbit.

Titan is a unique natural laboratory for organic chemistry, unlike any other environment in the solar system, and clearly the prime target for theme C—exploring organic-rich environments—and high-priority question 2, How far toward life does organic chemistry proceed in extreme environments? Titan's atmosphere not only creates this scientifically interesting environment, but also facilitates future exploration via aerocapture and airborne mobility. Titan may also have a subsurface water layer and could prove to be a promising location to search for past or extant life or its precursor chemistry, and it is important to several other themes and questions (see Table 5.3).

It cannot now be predicted whether Europa or Titan will ultimately prove to be the most promising satellite for long-term exploration. However, Cassini-Huygens will surely revolutionize our understanding of Titan, so it is premature to plan a subsequent Titan mission in detail. Another consideration is that any mission to the outer solar system requires a decade or more from the initial design to the end of the mission. Therefore, a logical approach is to continue to alternate between Europa and Titan missions that overlap in time. Cassini-Huygens followed Galileo, so the next mission should be to Europa, then a new mission to Titan. Any mission to Europa or Titan that significantly advances our objectives is likely to be expensive. International collaboration is important scientifically and may prove essential to adequately fund these endeavors.

The other large satellites are also providing significant exploration opportunities. Whole satellite systems must be studied in order to address theme A—the origin and evolution of satellite systems. Theme D—understanding dynamic planetary processes—leads us principally to Io and Triton in addition to Titan, as well as Ganymede, Europa, and Enceladus. High-priority questions 3 and 4 lead us to all of the six largest satellites and to Enceladus and Miranda.

Ground-Based Supporting Facilities

The panel recommends continued support for the IRTF along with the proposed adaptive optics upgrade in order to enhance the scientific results of the Cassini-Huygens exploration of Titan. While the IRTF will continue to provide necessary support for planetary astronomy, it is a relatively small telescope, and many future investigations require larger apertures, on the order of a ~20- to 30-meter-class telescope. The advantage of such a telescope, for example, GSMT, with an accompanying advance in adaptive optics techniques, is the increased spatial resolution and sensitivity to dim sources. A GSMT would provide about 18,000 resolution elements across the disk of Io at opposition, allowing the study of the energetics of Io's volcanoes by resolving many compositionally and energetically distinct regions on the satellite's surface (Figure 5.6). It would resolve large Titan storms, providing information on Titan's weather. The GSMT would clarify the vertical structure of Io's atmosphere through occultations. It would better characterize the spectra of dark, likely organic, solids on satellite surfaces. In addition, the GSMT would enable critical mission support: for example, if it were available, it could better determine Titan's wind field and thus lead to better tracking of the Huygens probe.

Summary of Panel Recommendations

Based on the summarized findings presented in Tables 5.2 and 5.3, the SSE Survey's Large Satellites Panel ranks its recommendations as follows.

Small Initiatives

1. Cassini-Huygens, with preparation for enhanced science analysis and an extended mission
2. Continued support for Earth-based telescopes, to include the acquisition of an appropriate amount of GSMT observing time

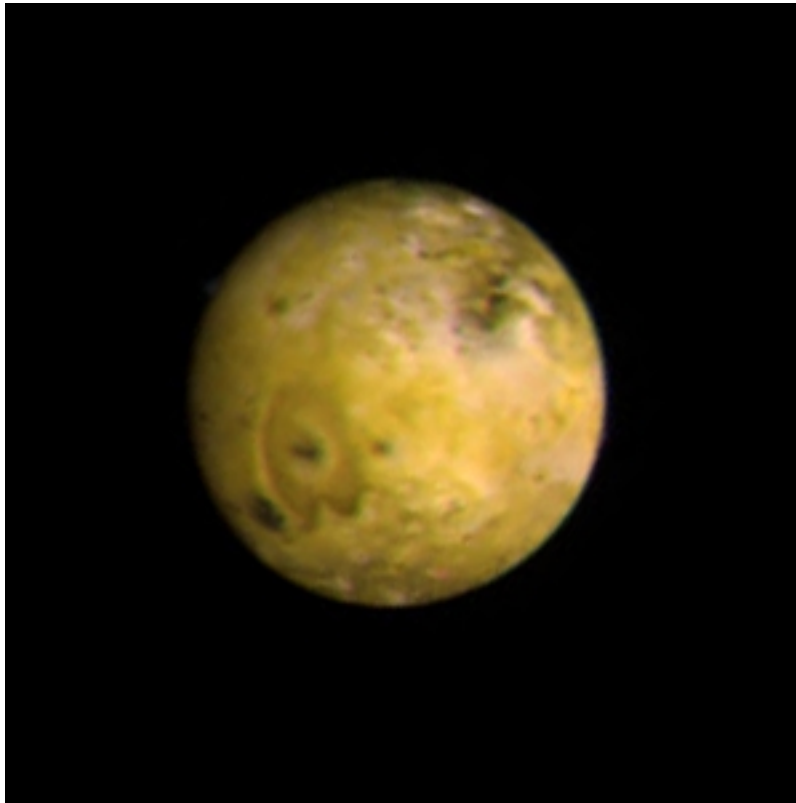


FIGURE 5.6 This Voyager 1 image of Io, the innermost of Jupiter's Galilean satellites, has a spatial resolution approximately the same as that from a 30-meter-aperture, Earth-based telescope equipped with active optics. Such a telescope would provide researchers with the ability to monitor the eruptions of Io's numerous volcanoes on a regular basis for a period of years to decades. The pear-shaped plume of the volcano Pele is just visible on Io's upper-left-hand limb in the original image. Courtesy of NASA/JPL.

Medium Initiatives

1. New technology developments to support future missions
2. Io Explorer
3. Ganymede Orbiter

Large Initiatives

1. Europa Geophysical Explorer
2. Titan Explorer
3. Europa Lander (Pathfinder or Astrobiology)
4. Neptune Orbiter

New Technology

Technology initiatives that are needed are ranked below and follow from the recommendations outlined above:

1. Radiation-hard electronics—for Europa Geophysical Explorer and future Europa landers and Io Observer,
2. Advanced telemetry and power systems—for all deep-space missions,
3. Atmospheric mobility—for Titan Explorer,
4. Compact organic chemistry laboratory—for Titan Explorer and Europa landers,
5. Planetary protection—for Europa landers,
6. In situ age-dating—for Europa landers and Titan Explorer, and
7. Solar-electric propulsion and aerocapture or nuclear-electric propulsion—for Neptune Orbiter.

Although the technology recommendations above follow logically from the panel's science and mission rankings, technologies may be developed for other reasons. For example, the administration's FY 2003 budget proposal includes funding for nuclear-electric propulsion. Once nuclear-electric propulsion is developed, this capability would then open up new mission possibilities, such as a spacecraft that could sequentially orbit all three icy Galilean satellites. Why not postpone the Europa Geophysical Explorer mission until nuclear-electric propulsion is available? There are several good reasons for not postponing this important mission. First, nuclear-electric propulsion is not expected to be ready for an actual mission for at least 10 years, and this panel considers Europa exploration too scientifically important to postpone it for a decade. Second, an orbiter around Europa is far more important for the panel's key objectives than are orbiters around Callisto or Ganymede, because Europa's tides are much larger (i.e., measurable via altimetry) and because its ice shell is significantly thinner (permitting radar sounding). Study of Callisto and Ganymede is important to understand this class of icy satellite, but multiple flybys of these two moons expected from the Europa Geophysical Explorer will provide key information on the surface morphology and composition, upper crustal structure, and magnetospheric interactions. The subsequent step in Europa exploration should be a landed mission, which also requires a Europa orbiting spacecraft, and nuclear-electric propulsion and other new technologies may then enable a more capable mission.

Finally, the panel emphasizes that strong support for adequate R&A is essential to all future initiatives.

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